

Stellar explosions powered by the Blandford-Znajek mechanism

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ABSTRACT

In this letter we briefly describe the first results of our numerical study on the possibility of magnetic origin of relativistic jets of long duration gamma ray bursters within the collapsar scenario. We track the collapse of massive rotating stars onto a rotating central black hole using axisymmetric general relativistic magnetohydrodynamic code that utilizes a realistic equation of state of stellar matter, takes into account the cooling associated with emission of neutrinos, and the energy losses due to dissociation of nuclei. The neutrino heating is not included. We describe the solution for one particular model where the progenitor star has magnetic field $B = 3 \times 10^{10}$ G. The solution exhibits strong explosion driven by the Poynting-dominated jets whose power exceeds 2×10^{51} erg/s. The jets originate mainly from the black hole and they are powered via the Blandford-Znajek mechanism.

Key words: black hole physics – supernovae: general – gamma-rays: bursts – methods: numerical – MHD – relativity

1 INTRODUCTION

The phenomenon of Gamma Ray Burst (GRB) has been puzzling astrophysicists for many years since its discovery in 1970s (Klebesadel et al. 1973; Muzets et al. 1974). The recent identification of long duration GRBs with supernovae (see Della Valle 2006, and Woosley & Bloom 2006 for full review) means that we are dealing with enormous amount of energy, $10^{51} - 10^{52}$ erg, released within a very short time, 2-100 seconds, in the form of highly relativistic collimated outflow (Piran 2005). Most of the current GRB studies are focused on the physics associated with production of gamma rays in such flows and their interaction with the interstellar medium or the stellar wind of the supernova progenitor. However, the central question in the problem of GRBs is undoubtedly the nature of their central engines. These powerful jets have to be produced as a result of stellar collapse, most likely by the relativistic object, neutron star or black hole (BH), formed in the center, and make their way through the massive star unscathed, remaining well collimated and highly relativistic.

The most popular model of central engine is based on the “failed supernova” scenario of stellar collapse, or “collapsar”, where the iron core of progenitor star forms a BH (Woosley 1993). If the progenitor is non-rotating then its collapse is likely to continue in a “silent” manner until the

whole star is swallowed by the BH. If, however, the specific angular momentum in the equatorial part of stellar envelope exceeds that of the last stable orbit of the BH then the collapse becomes highly anisotropic. While in the polar region it may proceed more or less uninhibited, for a while, the equatorial layers form dense and massive accretion disk. The gravitational energy released in the disk can be very large, more than sufficient to stop the collapse of outer layers and drive GRB outflows, presumably in the polar direction where density is much lower (MacFadyen & Woosley 1999). In addition, there is plenty of rotational energy in the BH itself

$$E_{\text{rot}} = \frac{M_{\text{bh}} c^2}{2} \left\{ 2 - \left[\left(1 + \sqrt{1 - a^2} \right)^2 + a^2 \right]^{1/2} \right\}, \quad (1)$$

where M_{bh} is the BH mass and $a \in (-1, 1)$ is its dimensionless rotation parameter. For $M_{\text{bh}} = 3M_{\odot}$ and $a = 0.9$ this gives the enormous value of $E_{\text{rot}} \simeq 8 \times 10^{53}$ erg.

The three currently actively discussed mechanisms of powering GRB jets in the collapsar scenario are the heating via annihilation of neutrinos produced in the disk (MacFadyen & Woosley 1999), the magnetic braking of the disk (Blandford & Payne 1982; Uzdensky & MacFadyen 2006), and the magnetic braking of the BH (Blandford & Znajek 1977). The potential role of neutrino mechanism is rather difficult to assess as this requires accurate treatment of neutrino transport in a complex dynamic environment of

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collapsar. The long and complicated history of numerical studies of neutrino-driven supernova explosions teaches us to be cautious. Numerical simulations by MacFadyen & Woosley(1999) and Aloy et al.(2000) have demonstrated that sufficiently large energy deposition in the polar region above the disk may indeed result in fast collimated jets. However, the neutrino transport has not been implemented in these simulations and the energy deposition was based simply on expectations. When Nagataki et al.(2006) utilized a simple prescription for neutrino transport in their code they found that neutrino heating was insufficient to drive polar jets.

A number of groups have studied the collapsar scenario using Newtonian MHD codes and implementing the Paczynski-Witta potential in order to approximate the gravitational field of central BH (Proga et al. 2003; Fujimoto et al. 2006; Nagataki et al. 2006). In this approach it is impossible to capture the Blandford-Znajek effect and only the magnetic braking of the accretion disk can be investigated. The general conclusion of these studies is that the accretion disk can launch magnetically-driven jets provided the magnetic field in the progenitor core is sufficiently strong. Unfortunately, the jet power has not been given in most of these papers and is difficult to evaluate from the published numbers. In the simulations of Proga et al.(2003) the jet power at $t \simeq 0.25$ s is $\simeq 10^{50}$ erg/s. The initial magnetic field in these simulations is monopole with $B \simeq 2 \times 10^{14}$ G at $r = 3r_g$, where $r_g = GM_{\text{bh}}/c^2$ (private communication).

The study of collapsars in full GRMHD is still in its infancy. Sekiguchi & Shibata(2007) studied the collapse of rotating stellar cores and formation of BH in the collapsar scenario. Their results show powerful explosions soon after the accretion disk is formed around the BH and the free falling plasma of polar regions collides with this disk. These explosions are driven by the heat generated as a result of such collision. However, the authors have not accounted for the neutrino cooling and the energy losses due to photo-dissociation of atomic nuclei. and the explosions could be similar in nature to the “successful” prompt explosions of early supernova simulations (Bethe 1990). Mizuno et al.(2004a; 2004b) carried out GRMHD simulations in the time-independent space-time of a central BH. The computational domain did not include the BH ergosphere and thus they could not study the role of the Blandford-Znajek effect (Komissarov 2004a). The energy losses have not been included and the equation of state (EOS) was a simple polytrope. These simulations were run for a rather short time, $\simeq 280r_g/c$ where $r_g = GM/c^2$, and jets were formed almost immediately due to unrealistically strong initial magnetic field.

In this letter we describe the first results of axisymmetric GRMHD simulations of collapsars where we use realistic EOS (Timmes & Swesty 2000), include the energy losses due to neutrino emission (assuming optically thin regime) and photo-dissociation of nuclei (see the details of micro-physics in Komissarov & Barkov 2007), use the computational domain that includes the BH horizon and its ergosphere, and run simulations for a relatively long physical time, up to 0.5s. The neutrino heating is not included.

2 COMPUTER SIMULATIONS

The simulations were carried out with 2D axisymmetric GRMHD code described in Komissarov(2004b). Since this code can deal only with time-independent spacetimes we are forced to start from the point where the central BH has already been formed inside the collapsing star. In the presented model the BH mass $M_{\text{bh}} = 3M_{\odot}$ and its angular momentum parameter $a = 0.9$. The mass density and the radial velocity of the collapsing star are described by the free-fall model of Bethe(1990) corresponding to $t = 1$ s since the onset of collapse (see equations in Komissarov & Barkov, 2007). The parameter C is set to 9 corresponding to most massive stars. This gives us the free-fall mass rate $\dot{M} \simeq 0.5M_{\odot}\text{s}^{-1}$. On top of this we endowed the free-falling plasma with angular momentum and poloidal magnetic field. The angular momentum distribution describes a solid body rotation up to the cylindrical radius $\varpi = 6300$ km. Further out the angular momentum is constant, $l = 10^{17}\text{cm}^2\text{s}^{-1}$. The magnetic field distribution is that of a uniformly magnetized sphere in vacuum, the radius of this sphere $r_1 = 4500$ km and inside the sphere $B = 3 \times 10^{10}$ G. These distributions are intended to describe the progenitor at the onset of collapse rather than at the state developed one second later. We utilize the Kerr-Schild coordinates of spacetime. The computational grid is uniform in polar angle, θ , where it has 180 cells. In the radial direction it is uniform in $\log r$, and has 450 cells. The inner boundary is located just inside the event horizon and adopts the free-flow boundary conditions. The outer boundary is located at $r = 25000$ km and at this boundary the flow is prescribed according to the Bethe’s model.

At the beginning of simulations the angular momentum of accreting gas is less than that of the last stable orbit, l_{iso} . It falls straight into the BH, and no disk is formed. However, the magnetic flux threading the BH gradually increases and so is the magnetic pressure. When the outer layers with $l > l_{\text{iso}}$ reach the BH the centrifugal force slows down their infall and the accretion disk is beginning to form around the BH. At the same time the accretion shock separates from its surface. The low angular momentum plasma of polar regions k.png falling straight into the BH after passing the accretion shock whereas the high angular momentum plasma fills the “bubble” above and below the disk (fig.1). Strong differential rotation within this bubble leads to amplification of the azimuthal component of magnetic field, the magnetic pressure grows and eventually overwhelms the ram pressure of free-falling envelope – the explosion begins. The BH is a key player in the process pumping electromagnetic energy into the bubble and the disk at the rate of $\simeq 2 \times 10^{51}\text{ergs}^{-1}$.

Figures 2 and 3 show the solution at $t = 0.45$ s, near the end of simulations. At this time, the solution exhibits two well defined polar jets surrounded by the magnetic cocoons of high pressure and low density. The magnetic pressure of these cocoons, which have been inflated by the jets, exceeds by more than six orders of magnitude the magnetic pressure in the collapsing star. These over-pressured cocoons drive strong bow shock (blast wave) into the star (right panel of fig.2). The mean propagation speed of the shock in the polar direction $v_s \simeq 0.18c$. Near the equator the stellar plasma compressed by the shock continues streaming downward with supersonic speed. At the equator and well outside of the accretion disk the stream coming from

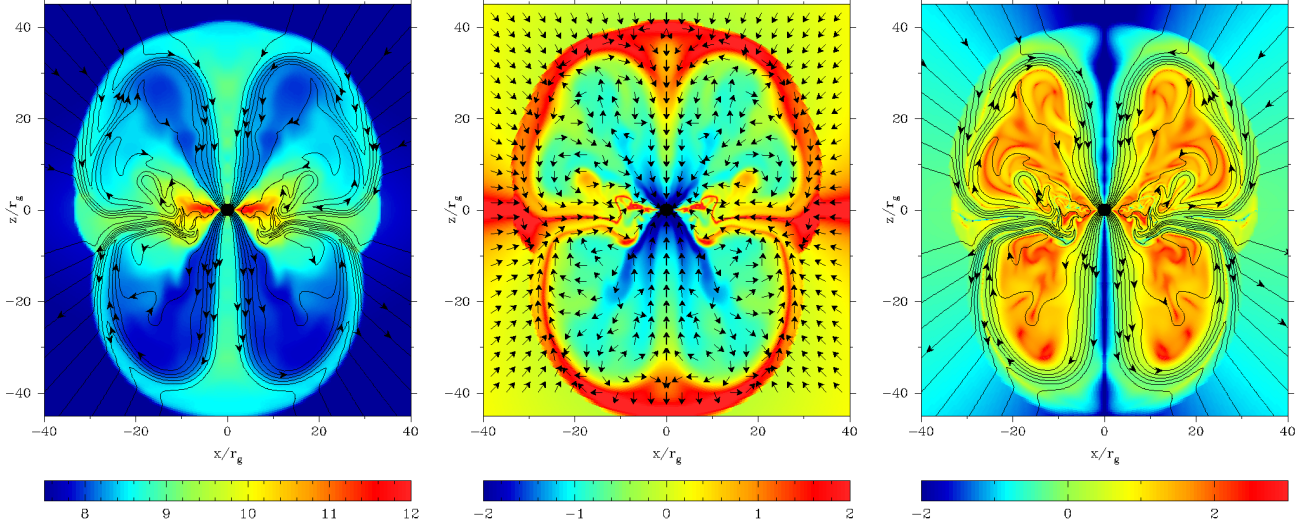


Figure 1. Solution immediately before the explosion ($t=0.24s$). Left panel: the baryonic rest mass density, $\log_{10}\rho$, in g/cm^3 and the magnetic field lines; Middle panel: the ratio of gas and magnetic pressures, $\log_{10}P/P_m$, and velocity direction vectors; Right panel: the ratio of azimuthal and poloidal magnetic field strengths, $\log_{10}B^\phi/B_p$, and the magnetic field lines.

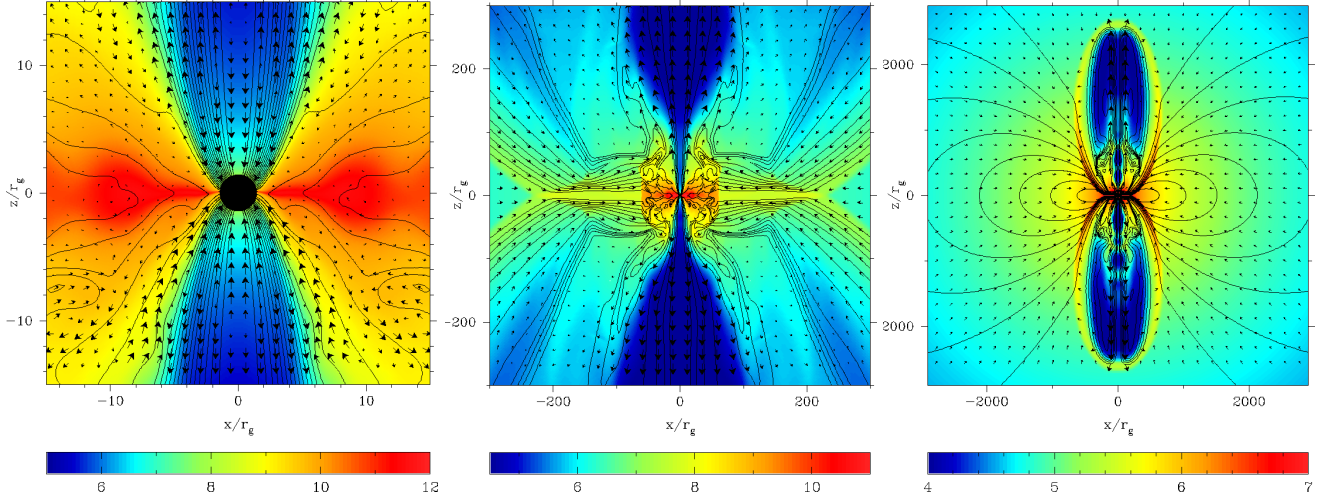


Figure 2. Solution on different scales at $t = 0.45s$. The colour images show the baryonic rest mass density, $\log_{10}\rho$ in g/cm^3 , the contours show the magnetic field lines, and the arrows show the velocity field.

northern hemisphere collides with the stream coming from the southern hemisphere and a pair of oblique shocks develop at $r \simeq 200r_g$ (middle panel of fig.3). These shocks are not strong enough to cause photo-dissociation of nuclei and the high post-shock pressure drives the reflected flows away from the equatorial plane. Plasma from the skin layers of the reflected streams actually enters the bubbles and interacts with the jets (We expect this effect to weaken later when the blast wave moves further away.) The inner layers of the reflected streams pass through another shock, at $r \simeq 50r_g$, and feed the accretion disk. The left panel of fig.2 shows the solution in the immediate vicinity of the BH. Its structure is reminiscent to that found in the previous studies of thick disks around BHs – main disk, its dynamic corona, and magnetically-dominated funnel (De Villiers & Hawley 2003; McKinney & Gammie 2004; Shibata et al. 2007). This

funnel is the region there the Pointing dominated jets are produced as well as the “wind” blowing into the BH – in this image one can clearly see the surface separating these flows.

Figure 3 shows the magnetic properties of the central region. Not only the funnel but also the disk corona are magnetically-dominated. The magnetic field strength reaches $\text{few} \times 10^{15}G$ near the BH, it is weaker in the funnel compared to the disk at the same spherical radius but not by much. Within the disk and corona the azimuthal magnetic field, B^ϕ exceeds the poloidal one, B_p , by two or three orders of magnitude. In contrast, in the funnel $B^\phi/B_p \leq 1$, reaching unity only near the funnel walls. In fact, the poloidal field in the funnel exceeds that in the disk and corona by 1-2 orders of magnitude. This is in contrast to the conclusion made by Ghosh & Abramowicz(1997) and Livio et al.(1999), namely

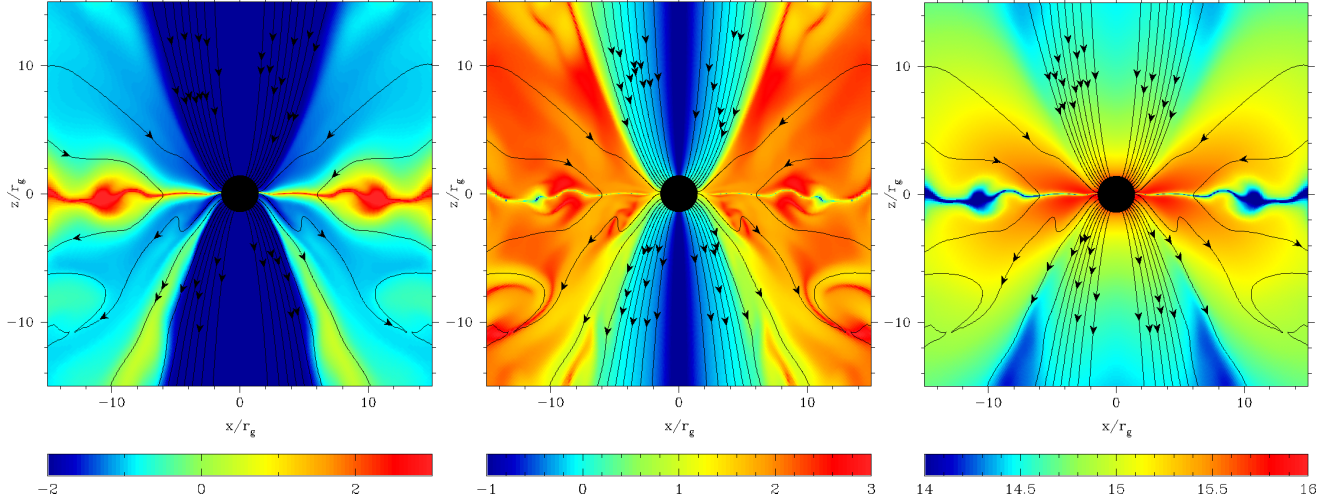


Figure 3. The inner region at $t = 0.45s$. Left panel: the magnetization parameter, $\log_{10}P/P_m$, and the magnetic field lines; Middle panel: the ratio of azimuthal and poloidal magnetic field strengths, $\log_{10}B^\phi/B_p$, and the magnetic field lines; Right panel: the magnetic field strength, $\log_{10}(B)$, and the magnetic field lines.

that the poloidal field threading the BH horizon should be of the same order as the poloidal field in the inner parts of the disk. Their main argument, that both fields are produced by the same azimuthal current flowing in the disk, misses the fact that additional currents may flow in the magnetosphere and over the disk/funnel surface and support the magnetic field inside the funnel in the manner similar to solenoid. In our case, the poloidal field threading the BH is the original field of the progenitor that has been accumulated during the initial phase of free infall.

The left panel of fig.4 shows the baryonic mass flux as a function of spherical radius. One can see that it reduces from the free-fall value $\dot{M} \simeq -0.5M_\odot s^{-1}$ down to $\dot{M} \simeq -0.06M_\odot s^{-1}$ at the event horizon. Between $r \simeq 60r_g$ and $r = 2500r_g$ this reduction reflects the effect of the bow shock driven into the star by the jets. The sharp reduction at $r \simeq 60r_g$ corresponds to the position of the accretion shock and marks the transition from approximate free-fall to the centrifugally supported disk.

The middle panel of fig.4 shows the integral energy fluxes of the jets as functions of spherical radius. To be more precise the integration is carried out over the whole sphere but the contribution from areas with the baryonic rest mass density $\rho > 10^8 \text{g cm}^{-3}$ is excluded. We have verified that the bulk contribution to the fluxes computed in this way comes from the jets. The baryonic rest mass flux, ρu^r radial component of 4-velocity, is excluded from the total and the matter energy fluxes, that is these fluxes are computed via

$$\dot{E} = -2\pi \int_S (T_t^r + \rho u^r) \sqrt{\gamma} d\theta, \quad (2)$$

where γ is the determinant of the metric tensor of space and \mathbf{T} is either the total stress-energy-momentum tensor or its hydrodynamic part. The most important conclusion suggested by this figure is that at least 80% of the jet energy is provided directly by the BH and at a very high rate, $\dot{E} \simeq 2 \times 10^{51} \text{erg s}^{-1}$. The remaining 20% seem to be provided by the inner part of the disk – this explains the rise of

jet power between the event horizon and $r \simeq 10r_g$. Indeed, careful examination of the solution shows that some magnetic field lines enter the jet from the skin layers of the disk with $\rho > 10^8 \text{g cm}^{-3}$. However, it remains to be shown that this is not caused by the numerical diffusion of magnetic flux from the funnel into the disk. The right panel of fig.4 shows the distributions of Poynting flux and hydrodynamic energy flux (including the rest mass-energy) across the horizon and allows us to determine whether it is the Blandford-Znajek or the MHD-Penrose mechanism (Punsly & Coroniti 1990; Punsly 2001; Koide et al.2002) or both of them that provide the energy supply to the jets. Since the hydrodynamic flux is everywhere negative the MHD-Penrose mechanism can be ruled out with certainty. This is confirmed by the fact that the hydrodynamic energy-at-infinity is positive everywhere inside the ergosphere. Thus the jet is powered by the Blandford-Znajek mechanism. For a force-free monopole magnetosphere the Blandford-Znajek power is given by

$$\dot{E}_{\text{BZ}} = \frac{1}{6c} \left(\frac{\Omega_h \Psi}{4\pi} \right)^2, \quad (3)$$

where Ω_h is the angular velocity of the BH and Ψ is the magnetic flux threading the BH. In the derivation we assumed that the angular velocity of magnetosphere $\Omega = 0.5\Omega_h$. This holds well even for rapidly rotating BHs with monopole magnetospheres (Komissarov 2001) and corresponds to the mean value of Ω measured in our simulations as well. Using the measured value of Ψ we derive $\dot{E}_{\text{BZ}} \simeq 2.6 \times 10^{51} \text{erg s}^{-1}$ which agrees quite well with the value of \dot{E}_{BZ} provided by fig.4. The total amount of free energy-at-infinity in the bow shock and the bubble at time $t = 0.45s$ is $E \simeq 1.37 \times 10^{51} \text{erg}$. Since the explosion develops only at $t = 0.24s$ the mean jet power over the active period is $\langle \dot{E} \rangle \simeq 6 \times 10^{51} \text{erg s}^{-1}$, indicating the higher jet power at the early stages of the explosion.

The middle panel of fig.4 also shows that initially the jets are Poynting-dominated but gradually the electromagnetic energy is converted into the energy of matter. However, the accuracy of our simulations is insufficient to capture the jet dynamics. First of all, we are forced to keep the flow magnetization below the limit at which the code crashes –

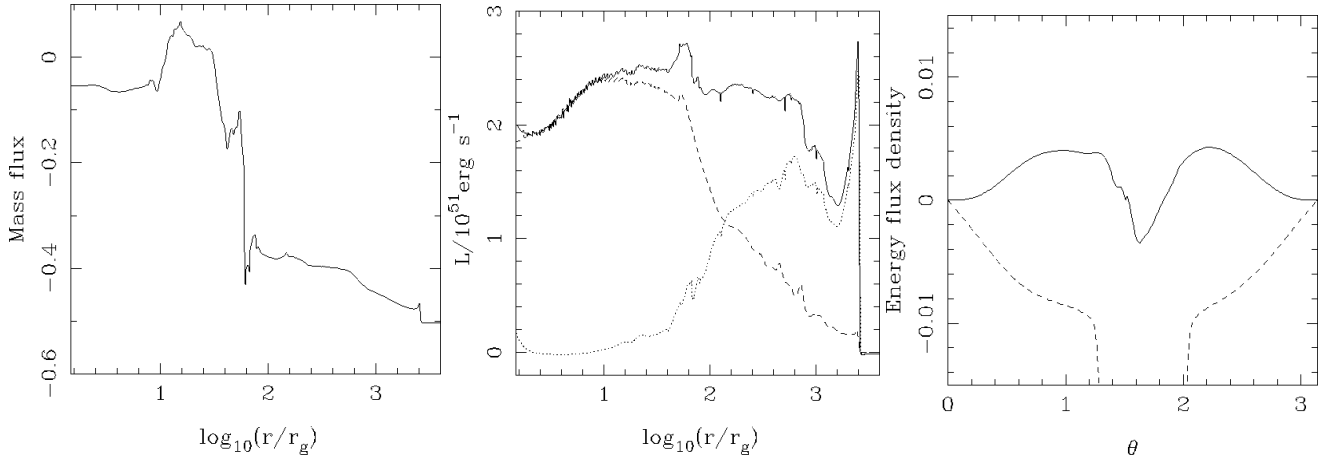


Figure 4. Left panel: the integral baryonic mass flux in units $M_{\odot} s^{-1}$ as a function of spherical radius; Middle panel: the integral fluxes of total energy (solid line), electromagnetic energy (dashed line), and hydrodynamic energy (dotted line); Right panel: the energy flux densities at the event horizon for electromagnetic energy (solid line) and hydrodynamic (matter) energy. Time $t = 0.45s$.

this is done via artificial injection of plasma in the danger cells. This reduces the length scale for the energy conversion via magnetic acceleration of plasma, as well as the asymptotic Lorentz factor. The numerical mass diffusion into the jets from the disk corona further exacerbates this problem. Finally, numerical resistivity causes dissipation of the jet electric current. Due to the mass diffusion and numerical viscosity the jets never become ultrarelativistic - their Lorentz factor rarely exceeds $\Gamma = 3$. On the other hand, the total energy is conserved we do not expect these numerical problems to have strong effect on the dynamics of the bow shock and the bubble inflated by the jets.

3 CONCLUSIONS

Our results provide strong support to the idea that magnetic fields can play a crucial role in driving powerful GRB jets and associated stellar explosions not only in the magnetar model but also in the collapsar model. The main energy source for the jets and explosions in our simulations is the rotational energy of black hole and it is released via the Blandford-Znajek mechanism. The measured rate of energy release, $\dot{E} \geq 2 \times 10^{51} \text{ erg s}^{-1}$, can explain the energetics of even the shortest of long duration GRBs. The fact that the rotational energy of black hole, $E_{\text{bh}} \simeq \text{few} \times 10^{53} \text{ erg}$, exceeds the typical explosion values derived from observations, $E \simeq 10^{52} \text{ erg}$, suggests a self-regulating process in which the black hole activity ceases when the blast wave terminates further mass supply to the accretion disk. The full details of the simulations together with the results of parameter study will be presented elsewhere.

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